

A novel time delay estimation technique for spread spectrum systems

5 THE BACKGROUND OF THE INVENTION AND PRIOR ART

The present invention relates generally to positioning of mobile units by means of radio signals. More particularly the invention relates to a method for determining a position of a signal transmitter according to the preamble of claim 1, a sensor according to the preamble of claim 12 and a system according to the preamble of claim 15. The invention also relates to a computer program according to claim 10 and a computer readable medium according to claim 11.

In modern life there are many situations in which an accurate positioning of a mobile unit is desirable, for instance in applications concerning freight, transportation, logistics and surveillance or when tracking soldiers and vehicles in a combat training area. In the latter case, the tracking data thus generated may either be used for later simulation or for online monitoring purposes. In any case, due to the normally harsh operating conditions, it is important that the tracking system be robust and provides a high degree of freedom of movement for the personnel and vehicles carrying the tracking units.

Today, there are a number of alternative solutions for accomplishing positioning data in respect of a mobile unit, which is associated with an individual or a vehicle. A GNSS (Global Navigation Satellite System, of any type) can potentially provide a high accuracy for outdoor applications, at least in the order of 10 cm. However, since the GNSS requires a line of sight to

multiple satellites, the system tends to be highly inaccurate in urban environments. Moreover, the system suffers serious performance degradation in the presence of radio channel multipath components.

- 5 An urban system or an indoor system may instead be based on the received signal strength of so-called radio propagation fingerprints. A calibrated systems based on such fingerprints may attain an accuracy of 1 m. However, the system requires that radio channel and strength measurements be made before
- 10 the system is established, and its performance is highly environment specific. Moreover, the system suffers from significant inaccuracies whenever the radio conditions are altered, for example as a result of pedestrian traffic or a change in the room arrangement.
- 15 Alternatively, a highly accurate system may be built on the basis of frequency references. This type of systems namely allows a very high accuracy in fixed line-of-sight conditions. However, such systems are very expensive, require oscillators of exceptionally high accuracy both at the transmitter and the
- 20 receiver end, and do not operate well in mobile environments. Furthermore, the design suffers from performance degradation in non-line-of-sight conditions.

- 25 It is also technically possible to accomplish positioning in a cellular infrastructure, such as that of a mobile telephone system. However, here the accuracy is limited to 10 m, or worse.

The U.S. patent No. 5,179,573 describes a system which utilizes a digital correlator to determine the time of arrival of a received pseudonoise signal. Based on the time of arrival, in turn, a distance to a signal transmitter may be estimated. The correlation is performed by means of a low-resolution correlator with a low complexity, wherein an incoming phase code pattern is matched against an internally stored phase code pattern. N-bit

in-phase and quadrature phase values are used to detect the time of arrival of the received signal. However, although the correlation process is iterative by involving one amplitude detection step and at least one time-of-arrival detection step, the 5 correlation performed is exclusively of auto-correlation type, i.e. a matching between the incoming signal and local copies in the receiver representing the possibly transmitted sequences. Since this requires an extensive over-sampling, the complexity of the iterative process proposed in the U.S. patent No. 5,179,573 10 increases very rapidly for each correlation iteration. Thus, in practice, an exceptionally large amount of processing power is required to attain a level of positioning accuracy, which is generally desired in many of today's urban and indoor applications.

15 SUMMARY OF THE INVENTION

The object of the present invention is therefore to provide a simple and robust radio positioning solution, which alleviates the above problems and thus offers output data whose accuracy can be made very high with a reasonable amount of processing.

20 According to one aspect of the invention the object is achieved by the position determining method as initially described, wherein the correlating step includes an over-sampling sub-step, a selecting sub-step and a cross-correlating sub-step. The over-sampling sub-step involves over-sampling the representation of 25 the received signal, at least within the uncertainty region, to obtain a corresponding over-sampled representation of the received signal. This over-sampling is equivalent to the use of a reduced chip period, which is shorter than the nominal chip period. The selecting sub-step involves selecting a local 30 spreading sequence, which contains poly-phased symbol values, i.e. non-binary values. The selected local spreading sequence has a nominal chip period, which also is equivalent to the reduced chip period. The cross-correlating sub-step involves corre-

lating the over-sampled representation of the received signal with the selected local spreading sequence, such that an improved uncertainty region is obtained which is more limited than one half nominal chip period.

- 5 This method is advantageous because thereby a relatively high spatial resolution is accomplished in a comparatively simple and processing efficient manner. For instance, the properties of the channel need not be considered. Moreover, the correlation optimization technique does not require amplitude examination.
- 10 According to a preferred embodiment of this aspect of the invention, prior to said cross-correlating sub-step, the correlating step involves an auto-correlating sub-step. This step achieves a chip level synchronization within an uncertainty region of one half nominal chip period around an auto-correlation peak by
- 15 correlating the representation of the received signal with a local copy of the transmitted spreading sequence. The auto-correlating sub-step is advantageous, since it renders it possible to reduce the size of a search window in which a more accurate delay parameter may be found. Thus, the processing efficiency
- 20 can be further improved. Depending on which type of signal was transmitted, the local copy used in the auto-correlating sub-step may a binary (i.e. biphase) signal, a quaternary signal or other poly-phase signal.

According to yet another preferred embodiment of this aspect of the invention, the method involves the steps of examining a phase difference function, which describes a phase difference between neighboring samples in a cross-correlation function resulting from said cross-correlating sub-step; and detecting a position in the phase difference function where the phase difference between neighboring samples exceeds a predetermined magnitude. The improved uncertainty region is then defined adjacent to samples in the over-sampled representation of the received signal, which are equivalent to the detected position in the phase difference function. By selecting the poly-

phased local spreading sequence appropriately said phase-difference change can be made very easy to detect, and consequently the definition of the search window can be made straightforward.

- 5 According to still another preferred embodiment of this aspect of the invention, sub-steps of over-sampling, selecting of a local spreading sequence and cross-correlating are repeated with progressively reduced chip periods and uncertainty regions until a desired limitation of the uncertainty region is achieved. A
10 different local spreading sequence is here selected for each over-sampling of the representation of the received signal. Again, this strategy is desirable because a high accuracy is obtained very efficiently.

According to a further preferred embodiment of this aspect of the invention, the reduced chip period with respect to a first over-sampling represents an over-sampling by an integer factor larger than one of the received direct sequence spread spectrum signal. Any subsequent over-sampling after the first over-sampling then represents an even larger over-sampling factor
20 than a foregoing over-sampling. Thereby, for each iteration, the resolution is increased efficiently at only a modest cost in terms of processing power. For example, a first over-sampling may be equivalent to a factor four, a second to a factor eight, and so on.

The over-sampling of the representation of the received signal
25 may either involve a linear interpolation between neighboring sampling points, or involve one or more repetitions of each sampling value. The latter strategy is more preferable, since it generally provides a better result, and is less complex to perform.

According to a further aspect of the invention the object is
30 achieved by a computer program, which is directly loadable into the internal memory of a computer, and includes software for controlling the above proposed method when said program is run on a computer.

According to another aspect of the invention the object is achieved by a computer readable medium, having a program recorded thereon, where the program is to control a computer to perform the above proposed method.

- 5 According to another aspect of the invention the object is achieved by a sensor as initially described, wherein the timing unit includes a sampling circuit, at least one bank of spreading sequences and a correlating circuit. The sampling circuit is adapted to over-sample the representation of the received signal, at least within the uncertainty region, and thereby produce a corresponding over-sampled representation of the received signal. The over-sampling is equivalent to the use of a reduced chip period, which is shorter than the nominal chip period. The at least one bank of spreading sequences is adapted to provide a local spreading sequence, which contains poly-phased symbol values being different from the set of symbols represented by the received signal. The local spreading sequence also has a nominal chip period which is equivalent to the reduced chip period. The correlating circuit is adapted to cross-correlate the over-sampled representation of the received signal with said local spreading sequence to obtain an improved uncertainty region being more limited than one half nominal chip period. A desirable feature of this sensor is that it enables a relatively high spatial resolution by means of simple and efficient hardware, which for instance, does not need to consider the properties of the channel.
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- According to a preferred embodiment of this aspect of the invention, the timing unit is adapted to, before cross-correlating the over-sampled representation of the received signal with said local spreading sequence, auto-correlate the representation of the received signal with a local copy of the transmitted spreading sequence from the at least one bank of spreading sequences, such that a chip level synchronization is obtained within an uncertainty region of one half nominal chip period around an auto-correlation peak. As mentioned above, such
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auto-correlation is advantageous because it facilitates an efficient reduction of a search window in which a more accurate delay parameter can be found.

According to a preferred embodiment of this aspect of the invention, the sensor includes a control circuit which is adapted to control the timing unit, such that for a particular representation of the received signal the at least one bank of spreading sequences provides an appropriate local spreading sequence to the correlating circuit. Thus, for each over-sampling, as well as for the initial band limited signal, correlation is performed between the representation of the received signal and a sequence which results in a high-quality estimation of the transmission delay. For example, a poly-phase sequence is selected whose resulting correlation function for a given over-sampling rate has a distinct phase-difference between consecutive values of the cross-correlation function.

According to another aspect of the invention the object is achieved by a system as initially described, wherein each of the sensors is a sensor of the above-proposed type. The advantages of the system according to the invention are apparent from the discussion hereinabove with reference to the proposed method and sensor.

The invention offers an excellent basis for providing an accurate, flexible and capable positioning system. For example, a positioning system designed according to the invention may cover a large number of buildings from a single location. Each of these buildings, in turn, may contain a very large number of separate rooms. Moreover, a positioning system based on the invention will be capable of handling a vast number of units (transmitters), which each is individually identifiable, has a low power consumption, and is small, lightweight, ruggedized as well as user safe. Such a system will be capable of providing a consistent accuracy and a high update frequency (i.e. number of measurements per unit). Furthermore, the invention renders it

comparatively easy to provide real-time data, and the invention makes it possible for users/units to join and leave a measurement area at arbitrary times. Finally, provided adequate hardware, a system based on the invention will be capable of handing over to and from an external GNSS-based system, such as GPS (Global Positioning System, owned by the U.S. Department of Defense and operated by the Air Force Space Command).

Further advantages, advantageous features and applications of the present invention will be apparent from the following description and the dependent claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is now to be explained more closely by means of preferred embodiments, which are disclosed as examples, and with reference to the attached drawings.

- 15 Figure 1 depicts an example of a system according to a preferred embodiment of the invention,
- Figure 2 shows a block diagram over a sensor according to a preferred embodiment of the invention,
- 20 Figure 3 illustrates, by means of a flow diagram, a general method for deriving a distance between a signal transmitter and a signal receiver according to the invention.
- Figure 4 shows a block diagram over a correlating circuit according to a preferred embodiment of the invention,
- 25 Figure 5 shows a diagram illustrating an idealized auto-correlation function of a spreading sequence,
- Figure 6 shows a diagram which exemplifies an auto-correlation function of a spreading sequence and a

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cross-correlation function between such a spreading sequence and a proposed poly-phase sequence suitable to determine an improved transmission delay parameter according to a preferred embodiment of the invention, and

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Figures 7a-b show diagrams which illustrate examples of a phase difference between the auto-correlation function and the cross-correlation function in figure 6, respective an absolute phase of said cross-correlation function.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

A proposed system is shown in figure 1. Here, a transmitter MT (e.g. a uniquely identifiable unit attached to a soldier) is presumed to be located in an area where a signal S_{MT} transmitted from the transmitter MT can be received by a plurality of sensors, say four, namely 100a, 100b, 100c and 100d respectively. The geographical position of each sensor is known with a high accuracy. According to a preferred embodiment of the invention, each of the sensors 100a, 100b, 100c and 100d determines a respective distance $D_{MT-100a}$, $D_{MT-100b}$, $D_{MT-100c}$ and $D_{MT-100d}$ to the transmitter MT based on a registered transmission delay of the signal S_{MT} . The distance data $D_{MT-100a}$ - $D_{MT-100d}$ is then forwarded from the sensors 100a, 100b, 100c and 100d to a central node 110, where the data is collected and used to calculate the transmitter's MT position by means of triangulation or similar technique, and with reference to the positions of the sensors 100a, 100b, 100c and 100d. Generally, the transmitter's MT position may be estimated more accurately if a large number of sensors are involved. Nevertheless, the signal S_{MT} must be received by at least three different sensors to enable determination of a two-dimensional position, and by at least four sensors to render three-dimensional position data $P_{xyz}(MT)$

possible.

Figure 2 shows a block diagram over a sensor 100 according to a preferred embodiment of the invention, which is adapted to determine a distance D_{MT-100} to a signal transmitter, such as MT 5 in figure 1, based on a direct sequence spread spectrum signal S_{MT} (e.g. binary or poly-phase) received from the transmitter. The sensor 100 includes a front end unit 210, a timing unit 220, a calculating circuit 230 and a control circuit 240.

The front end unit 210 is adapted to receive the signal S_{MT} in the 10 form of a propagated radio signal and deliver a band limited and time discrete representation thereof S_{BB} , which is sampled to fulfill the requirements of the Nyquist theorem.

The timing unit 220 is adapted to receive the representation S_{BB} 15 of the signal S_{MT} , and based thereon, estimate a transmission delay d of the signal S_{MT} . More specifically, the timing unit 220 determines the transmission delay d on the basis of a cross-correlation between at least one over-sampled representation $\langle S_{BB} \rangle$ of the received signal S_{MT} and at least one locally stored spreading sequence S_{PP} , which contains poly-phased symbol 20 values.

The calculating circuit 230 receives the transmission delay value d from the timing unit 220 and transforms this data into a corresponding distance D_{MT-100} between the transmitter, say MT in figure 1, and the sensor 100.

25 The control circuit 240 is adapted to control the timing unit 220 such that a particular over-sampled representation $\langle S_{BB} \rangle$ of the received signal S_{MT} is correlated with an appropriate local spreading sequence S_{PP} . Preferably, repeated cross-correlations are performed between various over-sampled representations $\langle S_{BB} \rangle$ 30 and local spreading sequences S_{PP} until a desired delay (/distance) resolution is obtained. A quality parameter q is fed back from the timing unit 220 to the control circuit 240 to indicate a current resolution, or timing accuracy of the received

signal S_{MT} .

- According to a preferred embodiment of the invention, the timing unit 220 includes a sampling circuit 221, two banks of spreading sequences 223a and 223b, and a correlating circuit 222. The 5 control circuit 240 and the timing unit 220 interact according to the following. Initially, the basic representation S_{BB} of the received signal S_{MT} is fed to the correlating circuit 222 together with a local copy S_{bin} of the (presumably) transmitted spreading sequence. The local copy S_{bin} is retrieved from a first bank of 10 spreading sequences 223b. The correlating circuit 222 correlates the signals S_{BB} and S_{bin} with one another (i.e. essentially performs an auto-correlation operation), and a corresponding transmission delay value d and quality parameter q are produced. Provided that the transmitted spreading sequence has 15 a particular nominal chip period, the quality parameter q would, after this correlation, typically indicate a chip level synchronization within an uncertainty region of one half nominal chip period around an auto-correlation peak in the resulting function (see 501 in figure 5).
- 20 If the control circuit 240 finds this degree of synchronization insufficient, it controls the timing unit 220 to perform at least one additional correlation operation. This time, a first control signal c_1 from the control circuit 240 instructs the sampling circuit 221 to over-sample the basic representation S_{BB} of the 25 received signal S_{MT} , at least within the above-mentioned uncertainty region, and (at least with respect to this region) produce a corresponding over-sampled representation $\langle S_{BB} \rangle$, say equivalent to an over-sampling by a factor four. However, any integer larger than one is equally well conceivable. In any 30 case, the chip period here becomes shorter than the nominal chip period.

A second control signal c_2 from the control circuit 240 instructs a second bank of spreading sequences 223a to deliver a local spreading sequence S_{PP} containing poly-phased symbol values.

The second control signal c_2 also activates a pair of switches 224 and 225, such that the over-sampled representation $\langle S_{BB} \rangle$ and the local spreading sequence S_{PP} are fed to the correlating circuit 222. Thus, this time, the correlating circuit 222 instead 5 cross-correlates the over-sampled representation $\langle S_{BB} \rangle$ of the received signal S_{MT} with the selected local spreading sequence S_{PP} . As mentioned earlier, given an appropriate local spreading sequence S_{PP} the result of the latter correlation improves the resolution, such that the uncertainty region becomes more limited 10 than one half nominal chip period. This is also reflected by an updated quality parameter q .

Naturally, if required, the control circuit 240 may instruct the sampling circuit 221 to deliver another over-sampled representation $\langle S_{BB} \rangle$ of the received signal S_{MT} (having a yet 15 higher sampling rate) and instruct the second bank of spreading sequences 223a to deliver a different local spreading sequence S_{PP} of poly-phased symbol values (which is appropriate with respect to said higher sampling rate), and repeat the cross-correlation. Such iteration may then be repeated until a satisfying 20 resolution is obtained.

In any case, the control circuit 240 is adapted to control the timing unit 220 such that for a particular representation S_{BB} or $\langle S_{BB} \rangle$ of the received signal S_{MT} one of the banks of spreading sequences 223a or 223b provide an appropriate local spreading 25 sequence S_{PP} or S_{bin} respectively to the correlating circuit 222.

Although the operating principle of the sensor 100, which is described above implies that an auto-correlation be performed before any cross-correlation is executed, the auto-correlation step may be omitted. However, the initial uncertainty region then 30 typically becomes larger than one half nominal chip period.

The general method for deriving a distance between a signal transmitter and a signal receiver according to the invention will now be described with reference to a flow diagram in figure 3.

- A first step 310 receives a direct spread spectrum signal, which has been transmitted from a unit within the system, for instance the transmitter MT in figure 1. As mentioned previously, the transmitted signal may have any type of format, such as binary, 5 quaternary or poly-phase. The step 310 also forms a representation of the received signal, for example by subjecting it to baseband sampling and filtering.
- A subsequent step 320 increases the sampling rate of the representation of the received signal. In a first run-through of the 10 procedure this increase is typically equivalent to an over-sampling by a factor four. However, again, any integer larger than one is conceivable. The over-sampling produces an over-sampled representation of the representation of the received signal.
- 15 Then, a step 330 selects an appropriate local spreading sequence that contains poly-phased symbol values, which are *different* from the set of symbols in the sequence used to spread the transmitted signal. A particular local spreading sequence is considered to be appropriate if it produces a cross-correlation 20 result together with the current over-sampled representation of the received signal, which has a distinct phase-difference change within a relatively narrow search window. Thus, the appropriate local spreading is not (necessarily) unique. Instead, a plurality of local spreading sequences may very well be appropriate, however more or less ideal.
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After that, step 340 performs a cross-correlation operation between the over-sampled representation of the received signal and the selected local spreading sequence. As a result, for example phase data are produced (a phase function and/or a 30 phase difference function). Step 350 examines whether it is possible to attain sufficient timing accuracy from the cross-correlation function and its associated phase data. If such an accuracy can be achieved on the basis of the latest performed correlation, the procedure continues to step 360. Otherwise, the

procedure loops back to the step 320 in order to further increase the oversampling rate.

- The step 360 estimates a transmission delay based on the cross-correlation performed in the step 340. On further basis of
- 5 the transmission delay a distance between the transmitter and the receiver is derived. Finally, this distance may be used as an input parameter when determining the transmitter's position. However, in order to determine a two-dimensional coordinate (e.g. represented by a geographical longitude and a latitude),
- 10 the transmitted signal must be received in at least three different sensors; and in order to determine a three-dimensional coordinate (e.g. represented by a geographical longitude and a latitude plus an altitude) the transmitted signal must be received by at least four different sensors.
- 15 All of the process steps, as well as any sub-sequence of steps, described with reference to the figure 3 above may be controlled by means of a programmed computer apparatus, preferably located in the proposed sensor. Moreover, although the embodiments of the invention described above with reference to the
- 20 drawings comprise computer apparatus and processes performed in computer apparatus, the invention thus also extends to computer programs, particularly computer programs on or in a carrier, adapted for putting the invention into practice. The program may be in the form of source code, object code, a code
- 25 intermediate source and object code such as in partially compiled form, or in any other form suitable for use in the implementation of the process according to the invention. The carrier may be any entity or device capable of carrying the program. For example, the carrier may comprise a storage
- 30 medium, such as a ROM (Read Only Memory), for example a CD (Compact Disc) or a semiconductor ROM, or a magnetic recording medium, for example a floppy disc or hard disc. Further, the carrier may be a transmissible carrier such as an electrical or optical signal which may be conveyed via electrical or optical cable or by radio or by other means. When the program is
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embodied in a signal which may be conveyed directly by a cable or other device or means, the carrier may be constituted by such cable or device or means. Alternatively, the carrier may be an integrated circuit in which the program is embedded, the 5 integrated circuit being adapted for performing, or for use in the performance of, the relevant processes.

Figure 4 shows a block diagram over a correlating circuit 222 according to a preferred embodiment of the invention. The correlating circuit 222 includes a conventional correlator 405 adapted 10 to perform auto-correlation operations with regard to a basic representation S_{BB} of the received signal. The correlating circuit 222 also contains at least one over-sampling correlator 410-415 adapted to perform cross-correlation operations with regard to over-sampled representations $\langle S_{BB} \rangle$ of the received signal. Each 15 correlator 405-415 produces a delay value d and a respective quality measure q_1, q_4 up to q_n . Moreover, according to this embodiment, a relevant over-sampling is accomplished within each over-sampling correlator 410-415. Thus, here the sampling circuit 221 of figure 2 is distributed inside the correlating circuit 222.

20 A first over-sampling correlator 410 represents an integer over-sampling larger than one (say four) of the representation $\langle S_{BB} \rangle$ of the transmitted direct sequence spread spectrum signal. Preferably, each subsequent over-sampling correlator up to the final correlator 415 after the first over-sampling represents an increased over-sampling by an integer factor (e.g. two) times a foregoing over-sampling. Consequently, the over-sampling correlators 410-415 may represent the over-sampling factors 4, 8, 16, 25 32, 64 etc up to n . A corresponding search window SW to be applied on each cross-correlation result is also illustrated in the 30 figure 4.

Figure 5 shows a diagram illustrating an auto-correlation function of an 11 chip binary Barker sequence, which may be used as a spreading sequence according to the invention. Although according to the invention, essentially any alternative spreading

sequence of any other length and format may also be used, the 11 chip binary Barker sequence is advantageous because it has good auto-correlation properties for conventional peak amplitude delay estimation. Moreover, it has the property of producing a
5 relatively constant reception of successive identical symbols.

The x-axis indicates a shift ΔT_c expressed in chip periods T_c , and the y-axis shows a normalized magnitude M_N . Of course, the function has a peak 501 (with a normalized magnitude value $M_N = 1$) at zero shift (i.e. $\Delta T_c = 0$). For all other shifts ΔT_c (i.e.
10 the side lobes) the normalized magnitude M_N is relatively low. The peak 501 is $2T_c$ wide, which means that an actual delay value for the received signal is to be found within an uncertainty region of one half chip period $T_c/2$ from the peak 501.

Figure 6 shows a diagram which exemplifies an auto-correlation
15 function of a spreading sequence [dotted line] (here a four times over-sampled 11 chip binary Barker sequence); and a cross-correlation function between such a sequence and a proposed poly-phase sequence [solid line], which is suitable to determine an improved transmission delay parameter according to a preferred embodiment of the invention. The x-axis indicates a delay d expressed in a number of samples from a central auto-correlation peak (at $d = 0$), and the y-axis shows absolute amplitude A . A $2T_c$ -wide search window SW is illustrated, which overlaps the central auto-correlation peak and within which the actual delay
20 value lies. As can be seen, the auto-correlation function has three (identical) symbols. Therefore, the function has three distinct peaks at $d \approx -48$, $d = 0$ and $d \approx 48$ respectively, and for all other values (i.e. between these peaks) the auto-correlation function has relatively low values. This makes it comparatively uncomplicated to detect the peaks. Moreover, averaging over several symbols is facilitated. Naturally, any number of consecutive identical symbols (other than the three symbols illustrated in figure 6) may also be transmitted. In fact, a relatively large number of such symbols are desired because then a greater degree of averaging
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improved.

It should be noted that the magnitude of the cross-correlation function at the correct delay must be reasonably large in order to obtain an acceptable performance in the presence of noise.

- 5 Figure 7a shows a diagram which illustrates the phase difference $\Delta\phi$ between the auto-correlation and cross-correlation functions of figure 6. The x-axis indicates a delay d expressed in a number of samples from the auto-correlation peak ($d = 0$), and the y-axis shows the phase difference $\Delta\phi$ expressed in radians.
- 10 An appropriate poly-phase sequence results in a relatively large phase difference in proximity to the auto-correlation peak (i.e. for $d = 0$) of approximately $\Delta\phi = 1,5$ radians, typically $\pi/2$. The theoretically largest peak value, however, is π .

- 15 Figure 7b shows a diagram, which along the y-axis illustrates an absolute phase angle ϕ (in radians) of the cross-correlation function in figure 6. The x-axis again indicates a delay d expressed in a number of samples from the auto-correlation peak ($d = 0$). As can be seen, the phase angle ϕ varies most between $d = -1$ and $d = 0$. This is an indication that the actual
- 20 delay value is likely to be located at $d = -1$, or at $d = 0$. Thus, an improved uncertainty region associated with the current over-sampling rate (and reduced chip period) should be defined over $d = -1$ (or possibly $d = 0$). It should be noted that the apparently large difference in the phase value between $d = -4$ and $d = -3$
- 25 simply depends on the selected reference angle. Namely, $\phi = \pi$ is the same as $\phi = -\pi$.

- The term "comprises/comprising" when used in this specification is taken to specify the presence of stated features, integers, steps or components. However, the term does not preclude the presence or addition of one or more additional features, integers, steps or components or groups thereof.

The invention is not restricted to the described embodiments in the figures, but may be varied freely within the scope of the claims.